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PACKAGING SYSTEMS INCLUDING RECYCLING

The influence of contaminants in the environmental impact of recovered paper: a life cycle assessment perspective

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Abstract
Purpose This study aims to analyze and quantify the environmental impacts associated with the production of testliner paper using 100 % recovered paper as fiber raw material, by applying the life cycle assessment principles. A simulation of advanced sorting technology was done to prepare and use batches of raw materials with different levels of contaminants. Comparative studies of environmental impact assessment were focused on the quality of recovered paper, which is decisively influenced by the efficiency of the sorting process. The particularity of the study is that so far it is the only one that analyzes the environmental impact generated by recovered paper quality.
Methods To analyze the environmental impacts in the scenarios, life cycle assessment methodology was considered. Potential environmental impacts were assessed by using the CML 2009, Dec.07 method developed by the Centre for Environmental Science from the University of Leiden.
Results and discussion In this study, acidification potential, abiotic resources depletion potential, eutrophication potential, global warming potential, photochemical ozone creation potential, and human toxicity potential were the impact categories analyzed. Considering that the system boundaries refer only to the paper mill that was obtained, all unitary processes involved in the manufacturing of product system influence in varying proportions the impact categories chosen for evaluation. A higher concentration of contaminants leads to a higher amount of energy and water used, and thus, a significant amount of waste and emissions generated. Simulations performed have highlighted the importance of sorting technology that influences the quality of raw material that will be used.
Conclusions Utilization of recovered paper batches with a low quality contributes to an increased environmental impact associated with the testliner paper manufacturing stage. A low quality of recovered paper will influence energy consumption in different modules of the system (recycled fiber pulp preparation, paper machine, and wastewater treatment), the volume of waste generated, and consequently the emissions released both in air and water.

Keywords Contaminants · Environmental impact · Life cycle assessment (LCA) · Recovered paper quality · Sorting technologies · Testliner

1 Introduction

Paper products manufactured and used in different spheres of activity worldwide have sparked the interest for environmental protection. In particular, this phenomenon has spread in the European paper industry which has adopted the concept of sustainable development (CEPI 2008, 2009). This is shown by several improvement and investments that have been undertaken both in technologies applied and raw material used, in order to improve the environmental performance. Specifically, the European paper industry has started to use recycled fiber widely, especially as recovery and reuse of paper has significant benefits. Studies developed by various researchers like Grossmann and Bilitewski (2005) and Moberg et al. (2007) or

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even by organizations such as the European Topic Center on Resource and Waste Management (2008) and the Integrated Pollution Prevention and Control (IPPC 2001) have shown that paper manufacturing from recycled fibers consumes less energy and water per ton of product and reduces carbon dioxide emissions and volume of generated waste. All this information has been also confirmed by a life cycle assessment study realized by Environmental Defense Organization (2002) from New York. Thereby, it was demonstrated that for papermaking from recycled fibers, the energy requirement is 1,880 TJ compared to 3,520 TJ for the processing of paper from virgin fibers, and the carbon footprint for recycled fibers is 0.14 kt CO_2 compared to 0.17 kt CO_2 in case of virgin fibers; data that have been introduced in BIR statistics (BIR 2008). With all these benefits, the quality is the major prerequisite for extending the use of recovered paper as a secondary raw material, that is directly influenced by the collection and sorting methods applied. Especially, sorting is the first stage after collection, when paper and board that are non-recyclable or unsuitable for the grade have to be removed (Bobu et al. 2010a, b). An efficient sorting of recovered paper has significant benefits especially by reducing the amounts of contaminants sent to the paper mill (Bosner et al. 2008). This will have a direct effect on the energy consumption in the processing stage (Bobu et al. 2010a, b) as well as on emissions and generated waste.

Taking into account these important aspects, the present work focused on studying the impact of unusable material content of recovered paper, on the amounts of waste generation and the electricity consumption in a recovered paper plant. Obtained results allow a prognosis regarding the importance of using quality raw materials whose effect will be positive on the environment.

2 Methodology

This study was conducted in accordance with the life cycle assessment (LCA) methodology, which is a suitable and valuable tool to assess the environmental impact of materials, products, and activities (Guinee et al. 2002). In accordance with the ISO standards, LCA methodology comprise four iterative steps, namely, goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation that have been followed throughout the study.

2.1 Goal and scope definition of the LCA study

2.1.1 Objectives

As stated above, the main objective of this paper is to quantify the benefits of advanced sorting technology of recovered paper, which is based on the analysis of environmental impacts in the manufacture of testliner paper from 100 % recovered paper.

From this overall objective, secondary objectives were derived such as:

1. Gather and build a set of environmental data related to analyzed system (paper mill)
2. Generate information on the environmental contribution to various indicators of individual processes that compose the system (LCA model)
3. Identify which environmental impact categories are mostly affected, as well as the substances that generate these impact and their relationship with the level of recovered paper quality and therefore the need for better sorting processes before being used as raw material in paper mill

Specifically, the study was based on a simulation of the advanced sorting technology of recovered paper in order to prepare and use batches of raw materials with different levels of contaminants, respectively, 4 % (P_0), 6 % (P_1), 8 % (P_2), and 10 % (P_3). Recovered paper batches were used in testliner paper manufacturing on paper machine from S.C. Vrancart Adjud. Simulation was done through a manual sorting process that took the current quality of recovered paper as its starting point for which inventory data have been collected based on questionnaire as annual averages for 2008. During the simulations, at the current quality of recovered paper, 5 % of contaminants was removed, respectively, and certain quantities of contaminants were added. Impurification of recovered paper batches was made with paper and board detrimental to production, especially beverage cartons.

2.1.2 Quality specifications for raw materials used in testliner paper manufacturing

Quality is a major condition for extending recovered paper use as raw material in paper industry (Bobu et al. 2010a, b), which is defined mainly by unusable material content (contaminants) and paper grades entering the composition (CEPI and ERPA 2002). As a general rule, to obtain new paper products, recovered paper used as a raw material must be clean and free of contaminants and with a moisture content which should not exceed 10–11 %. Beside these aspects, the recovered paper must be well sorted according to different criteria, where non-paper components, paper, and board that are non-recyclable or unsuitable for that have to be removed (Bobu et al. 2010a, b). Basically, the sorting methods and its efficency will determine the quality (type and content of contaminants) of recovered paper supplied to the paper mill.

For our particular case, recovered paper is collected from several suppliers and then transported to S.C. Vrancart S.A. Adjud paper mill, where it is sorted. Fixed quality specifications for recovered paper used by Vrancart Adjud are not available because the raw material comes from many suppliers. However, the European Standard EN 643 general rules for the receipt or refusal of all sorts of packaging are applied when the raw material is brought to the paper mill. The use of recovered paper in the manufacture of testliner paper respects the rules of receipt in the mills as follows: 10 % humidity, non-paper components (textiles, plastics, sand, metals, and glass)—max. 0.5 %, and paper and cardboard that are not in agreement with defined grades—max. 4 %.

2.2 Functional unit

This study focuses on the production of 1 t of testliner paper with following specifications: grammage (in grams per square meter)—110, humidity (in percent)—7.5, bursting (in kilopascals)—200, caliper (average value) (in micrometer)—180, roughness (average value) (in milliliters per minute)—900, and porosity (average value) (in milliliters per minute)—45. All the inputs and outputs from the inventory and impact results obtained in the life cycle assessment phase were expressed with reference to this functional unit.

2.3 Geographical and temporal references

This LCA study focuses on testliner paper manufacturing in Romania, the raw material being of Romanian origin. The study describes current situation in the testliner paper production using the most recently data.

2.4 System boundaries

In environmental impact assessment, special attention was given for each scenario to the processing stage in paper mill. This LCA study includes therefore an assessment of environmental impact in testliner paper production stage, from recovered paper transport to paper mill gate. Therefore, it does not include the distribution of the paper product, as well as the paper use and the papers' end-of-life. The main steps considered within the system boundaries are: (1) recovered paper transport from collection center to paper mill where raw material was sorted, (2) recovered paper pulp production (recycled fiber pulp), and (3) testliner paper manufaturing—situation evidenced in Fig. 1. Testliner paper obtained is used then to manufacture the corrugated board, for various packaging applications. However, the converting of corrugated board into packaging is excluded from the system boundaries as it is shown in Fig. 1. There are some steps that have not been included within the system boundaries like: (1) production and disposal of the infrastructure (machinery, vehicles, roads, buildings, etc.) and their maintenance and (2) impacts arising from the recovered paper feedstock (collected recovered paper), since it is impossible to determine the number of prior uses of the fiber in recovered paper.

At the mill scale, for simulating of the four scenarios, the impact of the contaminants on the amounts of waste generated and energy consumption was monitored in detail. This was done mainly by the progressive contamination with beverage

Fig. 1 System boundaries considered in this study

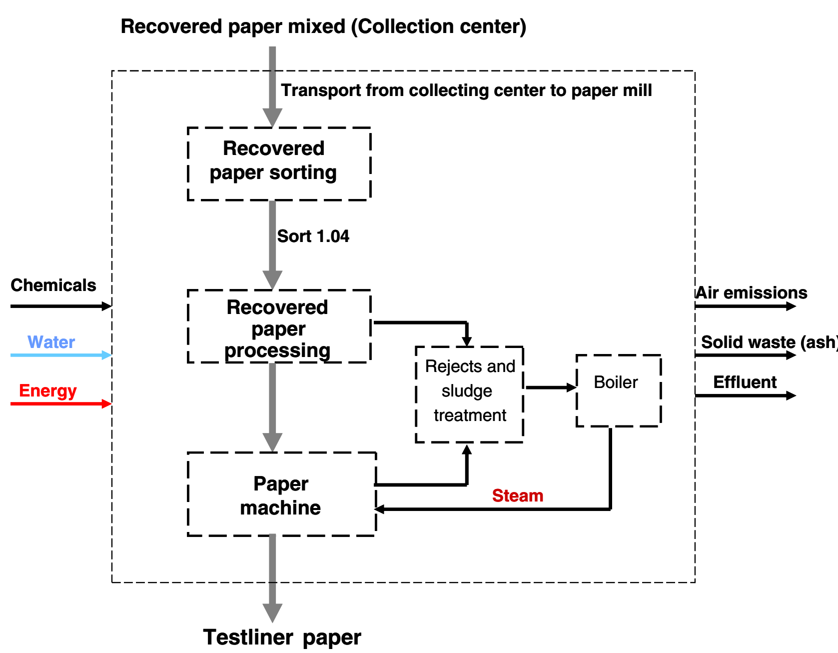

Table 1 Composition of raw material after contamination

Recovered paper quantity, kg	Contamination degree, %	Amounts of beverage cartons added, kg
1,109	4	44.36
1,153	6	69.18
1,214	8	97.12
1,316	10	131.6

cartons of recovered paper samples which previously were manually sorted. The quantities of contaminants added are presented in Table 1.

Recovered paper batches with various degrees of contamination were used in papermaking for a period of 20 h each. The organic wastes, represented by plastic and fibers from the sludge, were incinerated in special boilers to recover a good part of thermal energy. This explains why quantities of natural gas used are smaller from the first to the last scenario.

2.5 Key assumptions

As shown in Fig. 1, in the entire manufacturing process, the main stage is represented by the pulp production at paper mill, which includes specific operations: recovered paper defibration, coarse, and fine screening. All of these operations have resulted in wet solid wastes. To these, solid waste (rejects) from cleaning of pulp and sludge from wastewater treatment are added. For solid waste treatment, specific operations of each type of waste are applied.

Inventory data for transportation were calculated based on an average distance of 224.5 km/t of recovered paper. The truck used for analysis was considered to be 28 t of total capacity which is found in Ecoinvent database (Spielman et al. 2007) whose consumption is 35 l of diesel per 100 km. In case of energy, all energy inputs were considered.

2.6 Allocation

Allocation is the most critical issue in life cycle assessment (ISO 14044 2006) especially if the industry produce more products. For this reason, it was necessary to mention that in our case at S.C. Vrancart S.A. paper mill, the production line considered in this study produces a single type of paper: testliner. The only co-product that can also be obtained is the household and sanitary paper, but this has a very low percentage (0.06 %) of total production. Therefore, mass allocation was assumed taking into account the annual production.

2.7 Life cycle inventory

2.7.1 Data collection

In order to build the life cycle inventory, the collection of inventory data is the most effort-consuming step (Garcia Gonzales et al. 2011). More specifically, in the inventory stage, data for each simulated scenario have been calculated (4, 6, 8, and 10 % contaminant content). Data were calculated based on experiments conducted in the mill where the recovered paper batches with different degrees of contamination were used in papermaking for a period of 20 h each. Thus, during experiments, data regarding specific consumption of recovered paper, energy consumption, paper machine productivity, and volume of generated waste were calculated. Other primary data were calculated from the impact of the recovered paper quality to the final quality of the pulp that influenced energy, chemical and water consumption, waste volume from the preparation of pulp, and air and water emissions generated. By multiplying the average distance with the consumption of recovered paper per ton of paper produced, the distances have been obtained on which the recovered paper is transported to produce the functional unit. Also, because the model must be consistent with the limits of the system, environmental issues relevant to infrastructure, manufacturing, withdrawal from use of vehicles, etc. were eliminated. Whenever possible, secondary data (e.g., for chemicals) were also from databases, mainly Ecoinvent—a recognized database (Althaus et al. 2007)—which is integrated into the LCA software Gabi 4 (PE International 2006) used to perform this study.

2.7.2 Data analysis

All calculated and collected data were converted to values that relate to the functional unit established. Life cycle data analysis and modeling were done using the Gabi 4 software (PE International 2006).

3 Life cycle impact assessment

Life cycle impact assessment phase aimed at interpreting the results of the life cycle inventory. This interpretation indicated the ability of the paper product manufacturing stage to affect the environment. As stated above, life cycle impact assessment has resulted from the use of the GaBi 4 LCA software, issued by PE International GmbH (PE International 2006). The impact assessment was done by using the CML CML 2009, Dec.07 method (Guinee et al. 2002) developed by the Centre for Environmental Science, University of Leiden, Netherlands. For each scenario, flows, processes, and units were defined, which were finally connected to a graphical interface, called process plan. Unitary process of testliner

Table 2 Characterization results in absolute values for the impact categories analyzed in testliner paper manufacturing with variable content of contaminants

Impact category	Unit	Contaminant content			
		4 %	6 %	8 %	10 %
Abiotic resources depletion potential	kg Sb-eq.	6.04	6.02	6.01	5.98
Global warming potential	kg CO_2-eq.	687.41	721.85	782.72	847.50
Acidification potential	kg SO_2-eq.	15.98	16.45	17.51	18.67
Eutrophication potential	kg PO_4^{3-}-eq.	0.64	0.66	0.70	0.75
Human toxicity potential	kg DCB-eq.	222.17	223.54	229.99	232.93
Photochemical ozone creation potential	kg Ethene-eq.	0.88	0.93	0.98	1.04

DCB dichlorobenzene

paper manufacturing (recovered paper processing, paper machine, boiler, and reject/sludge treatment) at different levels of contamination was considered as a unique "black box" where raw material and energy are consumed and the end product and waste are generated.

According to LCA methodology in the first phase, the impact categories were selected together with the category indicators [units of each impact category, for example CO_2-eq. for global warming potential (GWP)] and the characterization model (which in our case is CML 2009, Dec.07). To establish the impact categories, which will be analyzed, the effects of the quality of recovered paper on energy consumption, volume of waste generated, and emissions released were taken into account. Of the mandatory steps included in the life cycle impact assessment phase, the classification and characterization were carried out.

In the classification phase, the results from the life cycle inventory data were attributed to the following selection of impact categories: abiotic resources depletion potential (ADP), GWP, human toxicity potential (HTP), acidification potential (AP), eutrophication potential (EP), and photochemical ozone creation potential (POCP). Later, in the characterization step, the results were calculated according to category indicators (for example: for GWP all emissions of CO_2, N_2O, CH_4, and other GHG gases have been converted to CO_2-eq. with a specific characterization factor for each substance).

4 Results and discussion

4.1 Characterization results

The results for the characterization step obtained for each impact category analyzed in the production of 1 t of testliner paper with variable content of contaminants, based on the CML 2009, Dec.07, are presented in Table 2.

4.2 Process contribution to impact categories

To highlight the influence of the unitary processes involved in testliner paper manufacturing at environmental impact, a detailed study of each scenario reviewed was also carried out. A first interpretation of the results was just done on the basis of the individual parameters and for each impact category analyzed the substances responsible for the environmental impact have been identified. Furthermore, a more detalied study of each impact category was carried out. Figures. 2, 3, 4, 5, 6, and 7 show the absolute values of the main processes that affect each impact category and, in correlations with the results, it is seen that four unitary processes have the most important contribution to all impact categories: electricity consumption, unitary process of testliner paper manufacturing, recovered paper transport from collection center to paper mill, and finally natural gas consumption.

Testliner paper manufacturing is the main important contributor to AP which to the scenario with 4 % contaminants has a absolute value around 11.31 kg SO_2-eq. and grows up to 14.22 kg SO_2-eq. in the last scenario with 10 % contaminants. By far, this unitary process is followed by natural gas consumption (boiler was used for supplementing fuel requirements at steam production) for which absolute values were obtained that vary between 2.58 and 1.8 kg SO_2-eq.; electricity consumption (at pulp and paper production, wastewater and reject management); and recovered paper transport. Increasing levels of contaminants lead to the

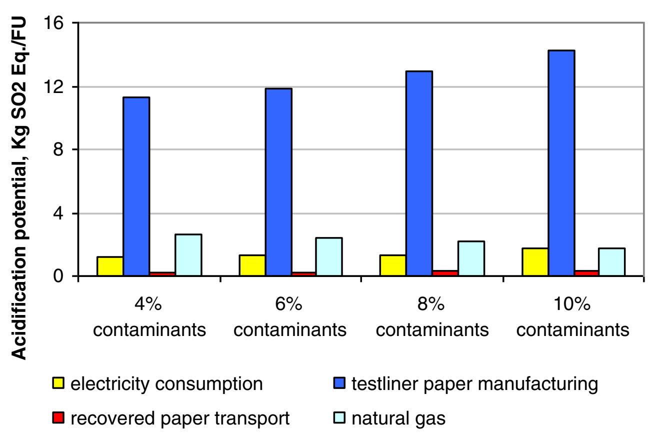

Fig. 2 Variations of the unitary processes that affect AP in testliner paper manufacturing at different levels of contamination

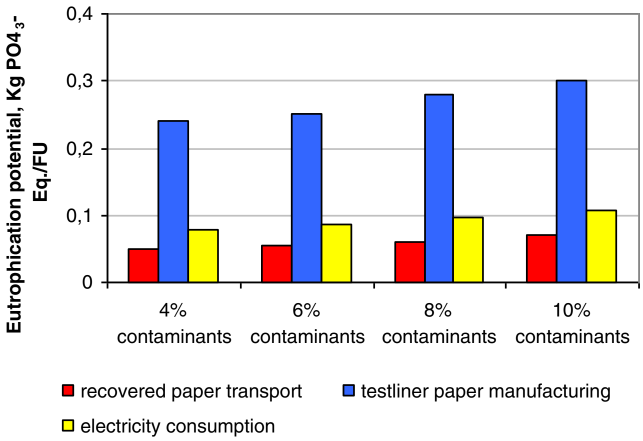

Fig. 3 Absolute values for the unitary processes that affect EP in testliner paper manufacturing at different levels of contamination

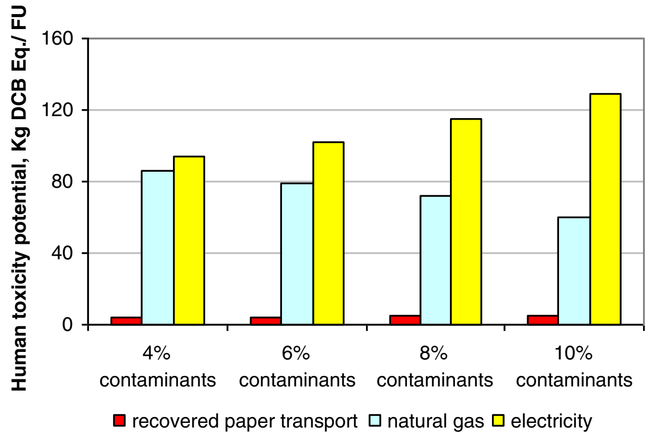

Fig. 5 Absolute values of the unitary processes that affect HTP in testliner paper manufacturing at different levels of contamination

production of larger quantities of acidifying substances emitted into the atmosphere, making use of raw materials which contain less contaminants to be more advantageous than that which contain 10 % contaminants. Emissions of SO_2 released by burning in special boilers for thermal energy recovery are the main contributing emissions to this impact category. Thus, the quantities of SO_2-eq. emissions released per functional unit ranged between 10.5 kg for the scenario with 4 % contaminants and 13.2 kg for the scenario with 10 % contaminants. SO_2 emissions have been also released from recovered paper transport stage by burning fuels that have high contents of S.

Figure 3 shows that majority of eutrophication potential is generated by unitary process of testliner paper manufacturing, whose absolute values on functional unit range from 0.24 to 0.3 kg PO_4^{3-}-eq. (see Fig. 3). Some also is generated by electricity consumption and recovered paper transport phase, for which absolute values have been obtained that are increasing from 0.07 to 0.10 kg PO_4^{3-}-eq., respectively, from 0.05 to 0.07 kg PO_4^{3-}-eq. Concerning the contributing emissions, airborne NO_2 emissions released at thermal energy recovery showed the greatest contribution to EP (quantities obtained increasing from 0.152 to 0.191 kg PO_4^{3-}-eq./functional unit (FU)), followed by those of COD and BOD to the water mainly derived after water treatment. Other important NO_2 emissions that affect the impact category were found to be released from recovered paper transport stage.

As shown in Fig. 4, the electricity consumption in pulp and paper production, wastewater, and reject treatment has a significant influence in GWP, with absolute values ranging from 310.93 kg CO_2-eq. in the first scenario to 424.88 kg CO_2-eq. in the last scenario. Testliner paper manufacturing unitary process and recovered paper transport phase are also responsible for impacts; for this last process, calculated values being 37.36 kg CO_2-eq./FU in the first scenario, 40.77 kg CO_2-eq./FU in the second scenario, 45.2 kg CO_2-eq./FU in the third scenario, and 53.11 kg CO_2-eq./FU for the fourth scenario. With increasing energy consumption, raw material, and water quantities, the contributions of the CO_2 emissions, dominant

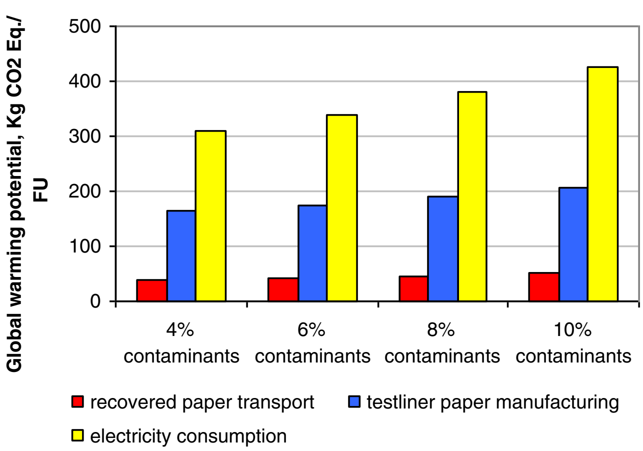

Fig. 4 Comparative absolute values for the unitary processes that affect GWP in testliner paper manufacturing at different levels of contamination

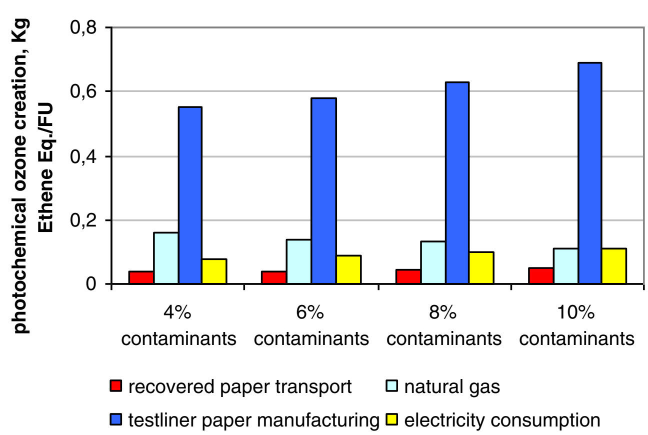

Fig. 6 Comparative absolute values for the unitary processes that affect POCP in testliner paper manufacturing at different levels of contamination

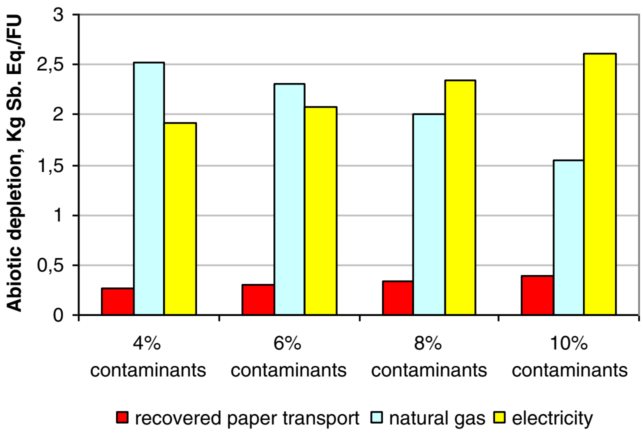

Fig. 7 Absolute values of the unitary processes that affect ADP in testliner paper manufacturing at different levels of contamination

substance in global warming potential, have also increased. For example, in the last scenario analyzed in which recovered paper batches have the main quantities of contaminants, the amount of carbon dioxide released was about 208 kg CO_2/FU.

Although we normally say that testliner paper manufacturing does not affect and should not have repercussions on human health (FPAC and PwC 2010), following detailed assessment of the human toxicity potential impact category (Fig. 5) could be seen that the unitary processes that affect mostly the impact categories are the consumption of electricity and natural gas. Thus, an absolute value which varies between 94.12 and 128.61 kg DCB-eq./FU may be associated with the electricity consumption. Because the quantities of natural gas used to complete the fuel requirements in the boiler for steam production are decreasing from scenario to scenario, for absolute values of the unitary process, a decrease was also obtained, respectively, from 86.4 to 60.48 kg DCB-eq./FU. If we refer only to the papermaking process in all the four scenarios, the human toxicity potential is less influenced by inorganic emissions of SO_2, NO, and dust particles, whose contribution to the environmental impact is quite small. The presence of heavy metals resulted from electricity production has been identified as causing an impact.

Once again, testliner paper manufacturing remains the main process that create POCP, whose values vary between 0.55 and 0.69 kg ethene-eq. The second largest contributor to POCP was the consumption of natural gas which for the first scenario has an absolute value around 0.16 kg ethene-eq., for the second scenario 0.14 kg ethene-eq., while for the third and fourth scenarios, it present absolute values of 0.13 and 0.11 kg ethene-eq., respectively. Less POCP is created in electricity consumption and raw material transport. SO_2 emissions (generated at thermal energy recovery) affect mostly the environmental impact; the quantities generated being between 0.50 and 0.63 kg ethene-eq. per functional unit.

Natural gas and electricity consumption, with recovered paper transport, have a significant influence on the abiotic depletion. For the electricity consumption, the obtained values ranged from 1.91 to 2.61 kg Sb-eq., for recovered paper transport between 0.27 and 0.39 kg Sb-eq., and finally because the natural gas was used in lower quantities from scenario 1 to scenario 4, values obtained for these have started from 2.52 kg Sb-eq. and have reached to 1.54 kg Sb-eq. The main substances which contribute to this impact category are non-renewable energy resources such as crude oil and natural gas, consumed in transport phase and electricity production.

5 Conclusions

This work has aimed to quantify the benefits of recovered paper sorting technology, which is based on the analysis of environmental impacts at the manufacture of testliner paper for corrugated board from 100 % recovered paper, by applying the LCA principles. The main unitary processes that influence the environmental impact of testliner paper manufacturing from batches of raw materials with variable

Table 3 Amounts of rejects resulted from testliner paper manufacturing from recovered paper batches with different degrees of contamination

Rejects from	Contaminant content, %							
	4		6		8		10	
	Generated	Landfilled	Generated	Landfilled	Generated	Landfilled	Generated	Landfilled
Dry sorting of RP, kg wet mass/t	2.5	2.5	2.62	2.62	2.86	2.86	3.14	3.14
Pulping/sorting, kg wet mass/t	75/146	50.2/97.8	120/233.6	80.4/156.5	175.9/342.5	117.8/229.4	259.5/505.1	173.8/338.4
Ash, kg dry matter/t	14.5	14.5	16.6	16.6	19.2	19.2	23.4	23.4

RP recovered paper

content of contaminants (4, 6, 8, and 10 %, respectively) were identified from the impact assessment results obtained and inventory analysis. Such main conclusions are described below:

- Utilization of recovered paper batches with a low quality will contribute to an increase of the environmental impact associate with testliner paper manufacturing stage. This is mainly due to the increase of energy consumption (a low quality of raw material involves a higher consumption of energy in pulp production, at paper machine and wastewater and reject management); volumes of generated waste and therefore more emissions released into the air and water. Table 3 presents the residual products generated and landfilled in the four scenarios simulated.
- An individual analysis of each impact category highlighted the following conclusions as follows:

– The unitary process of testliner paper manufacturing at different levels of contaminations influences major the acidification potential, of which the influences of natural gas and electricity consumption at paper mill are added
– The eutrophication potential is mostly due to the unitary process of testliner paper manufacturing, electricity consumption, and last but not least of raw material transport phase from collecting center to paper mill
– The electricity consumption in pulp and paper production and wastewater and reject treatment affect largely the global warming potential
– The electricity consumption to which natural gas consumption is added, used to obtain steam, is the main unitary process that affects human toxicity potential
– Once again, the unitary process of testliner paper manufacturing affects photochemical ozone creation potential in a largest proportion, followed by the natural gas consumption used to fill the need for fuel to produce steam at paper mill.
– Consumption of non-renewable energy resources dominates the abiotic depletion potential.

All these unitary processes were found to be significant sources of air and water emissions that affect the environmental impact.

The results obtained in environmental impact assessment lead to the conclusion that the implementation of an advanced sorting technologies of recovered paper from residential circuit is sustainable in terms of environmental impact. At the same time, the analysis of the main causes of the increase in the environmental impact with an increasing degree of recovered paper contamination (increased energy consumption, generation of a larger volumes of wet wastes, increasing of recovered paper specific consumption, and productivity reduction) shows that an advanced sorting can be efficient and economical. The social impact of new technology cannot be analyzed at this level, but with improvement of work conditions, the danger that the operators to come into contact with other contaminated products is decreasing; what is an argument to say that new technology can be sustainable in social terms.

6 Recommendations

The results emphasize the need for application of selective collection of paper and board and their advanced sorting stages that influence the quality of recovered paper grades supplied to paper mills. For the particular case of raw material used in testliner paper manufacturing, it was concluded that an efficient collection and an advanced sorting will achieve a high yield of wanted material and a high purity of each recovered paper grade which will be processed. While the performance of paper mill will increase, the global environmental behavior at testliner paper manufacturing will be improved. Therefore, it is important to have an adequate collection and classification of different types of paper for environmental improvement in processing.

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